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GEORGE R. AGASSIZ RADIO ASTRONOMY PREPRINTS

THE ELECTRICAL CHARACTERISTICS OF THE ATMOSPHERE AND SURFACE OF VENUS FROM RADAR OBSERVATIONS

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THE ELECTRICAL CHARACTERISTICS OF THE ATMOSPHERE AND SURFACE OF VENUS FROM RADAR OBSERVATIONS

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ABSTRACT

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Radar observations of Venus were made at wavelengths of 12.5 cm. and 68 cm. during several months around the 1961 inferior conjunction. These observations have been quantitatively compared for possible dispersion effects caused by the atmosphere of Venus and the interplanetary medium. A possible effect of the plasma has been observed at 68 cm through correlations of the radar echo characteristics with solar activity. On the assumption that this correlation was real, a crude model for the ionosphere of Venus has been developed. The model yields a maximum electron density at Venus of order 10^7 cm^{-3} corresponding to a plasma frequency of about 27 ~~30~~ Mcps. The absence of relative dispersion and absorption effects between the two propagation frequencies is interpreted to indicate that all plasma phenomena were small, however. In particular, the proposed "ionospheric" model as the source of the Venusian radio spectrum is shown to be inconsistent with the radar observations. An analysis of the observed echo power indicates the average dielectric constant of the Venusian surface material to be less than 7 but greater than 3 with no large upward variations during the observations. This low value of the dielectric constant and the absence of measurable variations in the echo power (and consequently, in the dielectric constant) is interpreted to indicate that there are no large bodies of water on the Venusian surface.

THE ELECTRICAL CHARACTERISTICS OF THE ATMOSPHERE AND SURFACE OF VENUS FROM RADAR OBSERVATIONS[1]

INTRODUCTION

Radar observations of Venus made at the 1961 inferior conjunction by the Jet Propulsion Laboratory and the Lincoln Laboratory have yielded significant information about the electrical properties of the Venus atmosphere and surface. The JPL group worked at a wavelength of 12.5 cm; the results have been documented by Victor and Stevens (1961), Muhleman (1961, 1962a) and Muhleman et al. (1962). The work of the Lincoln group at 68 cm is discussed by the Millstone Staff (1961), and by Pettingill et al. (1962).

This paper considers the fundamental results pertinent to the investigation of the atmosphere and surface electrical characteristics of Venus. The results may be summarized as follows:

1. The 12.5 cm reflection was from the solid surface of Venus (Muhleman et al. 1962).
2. The 68 cm reflection was from the solid surface of Venus (Pettingill et al. 1962).
3. A total of 11.2 ± 2.8% of the power that would have been reflected from an equivalent conducting sphere

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in vacuum with the same geometry as Venus was returned at 12.5 cm (Muhleman, 1962b).

4. Approximately 10% of the power at 68 cm was returned under the same assumptions (Pettingill et al. 1962).
5. The astronomical unit as determined by Pettingill at 68 cm is approximately 200 km shorter than that determined by Muhleman et al. (1962) at 12.5 cm.
6. There is no observed correlation on a daily basis between the returned echo power at 12.5 cm and the solar flare index or 10.7 cm solar flux.

Since results 1 and 2 are discussed in detail in the quoted references, nothing further will be added here except to emphasize that they are generally accepted as certainties. Results 3 through 6 will be discussed in detail.

I. THE IONOSPHERIC MODEL OF THE VENUS ATMOSPHERE

An excellent summary of information about the Venus atmosphere has been given by Mayer (1961). The fundamental information of interest for this study is the determination of the temperature of 285°K in the infrared and the equivalent black body temperature of 600°K in the spectral range from 3 to 12.5 cm; a range recently extended by Lilley (1961) to 21 cm. Several model atmospheres have been proposed that fit these observations (Barrett, 1961), (Öpik, 1961), (Tolbert and Straiton, 1962), (Sagan, 1960). A model found by Jones (1961) has received much discussion. It assumes a planetary surface temperature of about 285°K and a dense ionosphere with an electron temperature of 600°K. This model will be discussed in detail and shown to be completely inconsistent with the radar results summarized above.

If we assume that the equivalent black body surface temperature of Venus is T_s and that the atmosphere consists of electrons and ions with an electron temperature of T_e and a total opacity τ, the observed intensity at a frequency ν is given by

$$I(\nu) = I_s(\nu, T_s)e^{-\tau(\nu)} + I_e(\nu, T_e)(1-e^{-\tau(\nu)}) \quad . \tag{1}$$

We have assumed a plane-isothermal atmosphere for purposes of discussion. The exact expression for a spherical atmosphere can be written, but the results would not differ significantly. We may use the Rayleigh-Jeans approximation to the black body law for microwave lengths:

$$I(\nu, T) \cong \frac{2kT\nu^2}{C^2} \quad . \tag{2}$$

Then Eq. (1) becomes

$$T(\nu) = T_s e^{-\tau(\nu)} + T_e(1-e^{-\tau(\nu)}) \quad . \tag{3}$$

The opacity of the medium, τ , is assumed to be due to the electron-free-free-transition mechanism, and the absorption coefficient per cm is given by Oster (1961) as

$$K = \frac{8}{3} \left(\frac{\pi}{6}\right)^{1/2} \frac{e^6}{C(mkTe)^{3/2} \nu^2} \text{ Ne Ni} \left[\frac{\sqrt{3}}{\pi} \ln \left(\frac{4kT}{\gamma \nu h}\right)\right], \tag{4}$$

where

e = charge on the electron

k = Boltzman's constant

m = the electron mass

N_e = the electron density/cm^3

N_i = the ion density/cm^3

γ = 1.78...

The last term in brackets of Eq.. (4) can be identified with the so-called gaunt factor which we take to be 4.0 for the range of temperatures and frequencies considered here.

Insertion of the constants and the assumption that $N_e \simeq N_i$ yields

$$K = 7.91 \times 10^{-23} \frac{N_e^2}{T_e^{3/2}} \lambda^2 \quad (\text{cm}^{-1}) \quad . \tag{5}$$

The opacity is then

$$\tau(\lambda) = \tau(\nu) = 7.91 \times 10^{-23} \lambda^2 \int \frac{N_e^2}{T_e^{3/2}} dz \quad . \tag{6}$$

The fit to the observed radio spectrum near inferior conjunction as summarized by Mayer (1961) with $T_s = 285$ and $T_e = 600$ and

$$N_e^2 \; z = 4 \times 10^{25} \quad (cm^{-5})$$

is shown in Fig. 1. The model fits the observations well. However, the value of 4×10^{25} for the integral of the square of the electron density is very large by terrestrial analogy and by reasonable estimates of the solar flux, and atomic recombinations at Venus.

Table I shows the thickness d of the ionosphere for several values of the mean electron density that would yield 4×10^{25} as well as the ratio of the solid angle of the Venusian disk including the ionosphere to that of the visible disk. Thus if the electron density were 10^8 cm^{-3} the contributing disk would be 55 times the visible disk and would probably be detected in antenna-scanning operations. It is interesting to note that all the observations of the Venus effective temperature have been reduced by observers utilizing the visible disk and would be considerably in error. Therefore it appears that the mean electron density could not be much less than 10^9 cm^{-3} if the hypothesized ionospheric model were correct. Now, the electron density of the plasma that will correspond to the critical frequency at 68 cm is 2.4×10^9 cm^{-3}; i.e., at such densities the 68 cm waves would have been completely reflected contrary to the radar result of reflection from the solid surface.

Dispersion Effects

We now consider the significance of radar result 5 which concerns the close agreement in the determinations of the astronomical unit at 12.5 and 68 cm. The index of refraction n for a medium of electron density N_e cm^{-3} is given by Radcliffe (1959) as

$$n^2 \cong 1 - \frac{1}{1.24 \times 10^{-8}} \frac{N_e}{f^2} .$$

Thus the group velocity is

$$v_g \cong n c_0 ,$$

where f is the propagation frequency, and c_0 is the vacuum speed of light. Hence the index of refraction depends on the square of the wavelength, and the medium would cause a dispersion effect between the 12.5- and 68-cm waves.

1. If we assume the ionospheric model with $\int N_e^2 dz = 4 \times 10^{25}$ cm^{-5} and $N_e = 10^8$ cm^{-3}, the difference in the propagation time in terms of the astronomical unit for the two wavelengths is

$$A_{\oplus 68} - A_{\oplus 12.5} = +3360 \text{ km} .$$

2. If $N_e = 10^9$ cm^{-3}, then

$$A_{\oplus 68} - A_{\oplus 12.5} = +375 \text{ km} .$$

However, the radar results show that this quantity is minus 200 km. Actually, since the disagreement is within both probable errors (± 250 km) for the two astronomical unit determinations, probably no significant dispersion effects exist. However, Prof. F. Whipple (1962) has pointed out to the author that a correlation apparently does exist between the variations from the mean of the astronomical unit determinations at 68 cm (Pettingill et al.) and the 10.7 cm solar flux. Pettingill's residuals are shown in Fig. 2 along with the 10.7 cm solar flux. It should be noted that the solar flux has been plotted decreasing upwards. If an increase in electron density is associated with an increase in 10.7 cm solar flux, the group velocity would decrease and the measured values of the astronomical unit would lengthen contrary to the effects shown in Fig. 2. The formal correlation coefficient between the A. U. residuals and the solar flux was found to be minus 0.574 with a corresponding significance level greater than 99%. The correlation appears undeniable. No correlation has been observed between the solar flux and the 12.5 cm determinations. Further, the correlation between the returned signal power at 12.5 cm, and the solar flux was found to be statistically insignificant.

Pettingill et al. (1962) have pointed out that the variations in their residuals are of the correct period and phase with the Earth-Moon rotation. This suggests a possible error in the Earth-Moon center-of-mass position. Such an error would have to be due to an erroneous Earth-Moon mass ratio but the explanation is unacceptable for two reasons: first, the error in the mass ratio would have to be a factor of ten larger than the presently accepted uncertainty in this constant; and second, such an effect would persist through the observational period, contrary to the results shown in Fig. 2.

The acceptance of the hypothesis that the 10.7 cm solar flux is negatively correlated with the mean electron density suggests that the fundamental solar activity causes either a "sweeping out" of the electrons or an increase of recombinations, i.e., a proton flux. A crude model of the Venusian ionosphere can be constructed from a quantitative consideration of the data presented in Fig. 2. The rms value of the A. U. residuals is ± 210 km, which corresponds to an error in the Venus-Earth distance of about ± 60 km. The relative change in this distance caused by a change in the mean electron density will equal the relative change in the (group) index of refraction, i.e.,

$$\frac{\Delta z}{z} = \frac{\Delta n_g}{n_g} \simeq \Delta n_g \quad .$$

Since

$$n \simeq 1 - 0.40 \times 10^8 \frac{N_e}{f^2} \quad ,$$

we interpret Δn_g as

$$\Delta n_g = + 0.40 \times 10^8 \frac{N_e}{f^2} \quad .$$

Therefore

$$\Delta z = 0.40 \times 10^{8} z \frac{N_e}{f^2} .$$

Inserting f = 440 Mc, we may write

$$\Delta z = 2.06 \times 10^{-10} z N_e \text{ cm}$$

and finally

$$zN_e = 3 \times 10^{16} \text{ cm}^{-2} .$$

This value of the integrated electron density between the surfaces of the Earth and Venus may be compared to the Earth-Moon integrated density of about 10^{12} cm^{-2}. Thus only a negligible part of the Earth-Venus value can be due to the Earth's ionosphere, and the remainder must be attributed to the Venusian ionosphere and the interplanetary medium. If we assume an exponential distribution of electron density with distance from Venus of the form of

$$N_e = N_{e♀} e^{-kz} ,$$

the integrated electron density between Venus and the Earth is given by

$$\int_0^{Z_\oplus} N_e dz = N_{e♀} \int_0^{Z_\oplus} e^{-kz} dz .$$

We may solve for the scale height, k^{-1}, by setting this integral equal to 10^{16} cm^{-2} if we can estimate $N_{e♀}$. Since maximum density in the Earth's ionosphere is of order 10^6 cm^{-3}, we will assume a value, $N_{e♀} \simeq 10^7$ cm^{-3}. The calculations then yield a scale height of 10^4 km (less than 2 Venusian radii). The integrated-square electron density between Venus and the Earth is then $\int N_e^2 dz \simeq 5 \times 10^{22}$ cm^{-5} which is in good agreement with the empirical results presented below. The reader should realize that these values would correspond to an extensive ionosphere by terrestrial standards but far smaller than that required for the ionospheric model of Jones. The value $\int N_e^2 dz = 5 \times 10^{22}$ cm^{-5} yields an optical depth of about unity at 68 cm if we assume an electron temperature of 10^3 degree. As will be seen, this opacity is barely consistent with the radar observations and certainly is an upper bound.

If the value of the integrated-electron density is of order 10^6 cm^{-2} an excellent opportunity exists for the determination of the magnetic field of Venus. The Faraday rotation of the plane of polarization for a linearly polarized wave is given by the well-known relationship

$$\phi = \frac{4.72 \times 10^4}{f^2} \int H \cos \theta \; N_e dz \quad ,$$

where H is the magnetic intensity in gauss, θ the angle between the lines of the magnetic field and the propagation vector, and f the frequency in cps. For a radar reflection experiment conducted at 12.5 cm (thus avoiding any measurable rotation in the Earth's field), ϕ is given by

$$\phi \simeq 8.32 \times 10^{-15} \langle H \rangle zN_e \quad .$$

Utilizing $zN_e = 10^{16}$ cm^{-2}, we find that

$$\phi \simeq 10^2 \langle H. \rangle \quad .$$

Thus if ϕ can be measured to an accuracy of 10 degrees (approximately the current capability) the Venusian magnetic field can be detected if the field averaged over the electron distribution is greater than 10^{-3} gauss. Should the average field be of an order of magnitude larger than 10^{-3} gauss the polarization measurements would be ambiguous ($\phi > \pi$). However, such a field can be resolved in principle by radar techniques utilizing two closely-spaced transmission frequencies.

It should be noted that a maximum electron density at Venus of 10^7 cm^{-3} would correspond to a plasma frequency of about 27 Mc/s. In principle, the validity of this model can be checked by radio and radar techniques at frequencies above the terrestrial-plasma frequency and below 27 Mc/s.

An entirely different argument can be advanced as an explanation of the observed time-of-flight variations in the 68 cm radar observations. The electron density of the interplanetary medium is at present poorly determined even in the vicinity of the Earth's orbit. Recent work on the orientation of comet tails by Brandt (1962) suggests that the electron density in the vicinity of the Earth's orbit is considerably less than 50 electrons/cm^3. However, Schmidt and Elsässer (1962) using recent work on the zodical-light data have shown that the upper limit of the electron density near the Earth's orbit is at least 400 cm^{-3}. The discordance in results is unexplained. However, if we assume that the correct value is indeed 400 cm^{-3} and adopt an inverse-square dependence of N_e with distance from the sun, the integrated-electron density between the Earth and Venus is found to be 2.4×10^{15} cm^{-2}. This value is within an order of magnitude of that required to explain the radar observations. The integrated-squared electron density for the model is found to be 1.4×10^{21} cm^{-5} and the density at Venus is ~ 800 cm^{-3}.

Thus both of the above models are capable of explaining the radar observations. It should be emphasized, however, that our interpretation of the radar data is quite speculative and, consequently, the calculation of models may be premature.

Absorption Effects.

Another powerful argument against the ionospheric model can be made by considering the absorption of the radar signal power. Loss in signal power relative to a conducting sphere in a vacuum is caused by: (1) losses in the Earth's atmosphere; (2) losses in the interplanetary medium; (3) losses in the Venus atmosphere; and (4) losses at reflection from the Venusian surface. The losses from effects 1 and 2 are negligible at the wavelengths considered here. Losses by 3 depend on the square of the wavelength, and the losses by 4 are probably independent of the wavelength if we assume reasonable surface materials. Considerations of the scattering law for the surface at these frequencies are not important for this discussion. Thus results 4 and 5 as stated in Section I, showing that the reflected power was nearly the same at the two wavelengths, immediately suggest that the absorption in the Venus atmosphere is not large. In this discussion we assume that the only important absorption mechanism is the free-free electron process and neglect collisions with neutral particles, etc.; our arguments are thus conservative. If we assume that $\int N_e^2 dz$ is 4×10^{25} cm^{-5} and $T_e = 600°K$, we immediately get the absurd result that the loss on the 12.5 cm radar signal would be

$$e^{-2\tau} = e^{-66} \quad .$$

Therefore we conclude from the absence of dispersion effects at 12.5 and 68 cm and from the excessive absorption at both frequencies that the ionospheric model is not acceptable. It may be argued that the above analysis holds only for the region around the anti-subsolar point since the radar observations were made near inferior conjunction. The observations of the JPL group ran from March 22 to May 8, 1961, whereas those of the Lincoln group extended to early June, nearly to elongation. In the period from March 22 to May 8 about 67% of the Venus disk was covered by the line from the radar to the center of Venus as Fig. 3 shows. Of course the entire disk of Venus was covered by the transmitted radar wave but the returned power was primarily from a "cap" on the planet's surface centered about the line of sight from the radar. The exact size of this cap depends on the planetary rotational rate and the surface scattering law (Muhleman, 1962b). Kelloggand Sagan (1962) have qualitatively suggested that the lack of variations in the radar reflection power with the planetary phase angle could be due to a "hole" in the ionosphere of Venus centered on the anti-subsolar point. However, this argument is untenable. Fig. 4 shows the computation of an ionospheric model for such an ionosphere with a hole over 67% of the disk for Venus at conjunction along with the microwave black body observations. The parameters for this model are: $\int N_e^2 dz = 10^{26}$ cm^{-5}, $T_e = 1200$°K, and the surface temperature $T_s = 300$°K. However, this model would exhibit a strong change with changing Venusian phase angle. In fact, when Venus is at the east and west elongations the observed black body temperature would be approximately 1000°K for wavelengths of 10 cm and greater because more than half of the disk would be an opaque plasma at 1200°K. Such a phase effect is contrary to the observations of Mayer (1961) and Lilley (1961). This model, then, must also be rejected.

II. UPPER LIMIT ON THE INTEGRATED ELECTRON DENSITY

The altitude profile of the electron density for the Earth presented by Berning (1960) was numerically integrated to obtain approximate values for terrestrial analogies. These integrations yielded

$$\int N_e dz = 2.5 \times 10^{12} \ (cm^{-2})$$

and

$$\int N_e^2 \, dz = 5 \times 10^{18} \ (cm^{-5})$$

A value no more than twice as large as the first integral was inferred from work done by Evans (1957) whose utilization of lunar radar reflections suggested that the above value for the integrated square electron density is reasonable. We conclude that the terrestrial value is not much different from 10^{19} (cm^{-5}). Such a value for the Venus ionosphere would, of course, cause no measurable differential effects at 12.5 and 68 cm, a circumstance which would be consistent with the observations. It is interesting to consider the possibility of errors in the measured values of the power reflection. A careful consideration of the techniques employed by the two groups suggests that the widest reasonable errors in these determinations could put the power reflection at 12.5 cm at 20% and that at 68 cm at 5%. It should be realized that these values are very unlikely. If we then assume that the Venusian surface power reflectivity is R_s for both wavelengths, the atmospheric absorption can be found from the two equations

$$R_s e^{-2\tau_{12.5}} = 0.20 \qquad (7)$$

$$R_s e^{-2\tau_{68}} = 0.05 \qquad (8)$$

which yield

$$\tau_{68} - \tau_{12.5} = 0.695 \quad .$$

Then from Eq. (6) we get

$$\frac{1}{T_e^{3/2}} \int N_e^2 dz = 2.52 \times 10^{18} \quad .$$

Table II presents values for the integrated square electron density for a range of values of T_e and the ratio of this value to the terrestrial value of 10^{19} as well as the ratio of the mean Venusian electron density to that of the Earth, where we have assumed that the thickness of the ionospheres is the same for both planets. This supposition appears reasonable to within an order of magnitude. The electron temperature in this analysis is the mean temperature over the ionosphere since it has been taken out of the integral in Eq. (6). Furthermore, only a highly unlikely hypothesis would allow the reflection percentages to be in error by a factor as large as 2 and in opposite directions.

We conclude from the analysis that the mean electron density in the Venus atmosphere is less than two orders of magnitude greater than the terrestrial value and probably no more than one order of magnitude greater.

III. SURFACE PROPERTIES

The interpretation of the power reflection coefficient from the 68 cm data for Venus has been discussed by Pettingill et al. (1962). The fundamental theory for the reflection of radio waves from the Earth's surface has been given by Stratton (1941) and Kerr (1951). They show that with the assumption that the magnetic permeability of the material is equal to that of free space the power reflection coefficient for normal incidence is

$$R_s = \left[\frac{1 - \sqrt{\epsilon}}{1 + \sqrt{\epsilon}} \right]^2 , \qquad (9)$$

where ϵ is the standard dielectric constant. Equation (9) has been applied to the lunar radar case by Senior and Siegel (1959). The application of Eq. (9) is difficult because the effective scattering area for Venus or the Moon is not known. The radar cross-sectional area for a smooth (conducting) sphere large compared with the wavelength is equal to the real cross-sectional area of the sphere. However, if the sphere behaves as a rough scatter (Lambert) the radar cross-sectional area is increased by a factor of 8/3. Both Venus and the Moon are apparently smooth at decimeter wavelengths, and the former case is more nearly correct.

Equations (7) and (8), formally solved for the reflection coefficient, may (hopefully) yield an upper bound for the radar reflection percentage. We can make the solution if we can assume that the opacities at 12.5 and 68 cm are related in some known way; e.g., by the square of the wavelength for the free-free mechanism. The data reveal that if the opacity variation with wavelength is greater than the first power of λ then the absorption at 12.5 cm must be negligible when compared with that at 68 cm. If we assume that this variation goes as λ^2, the analysis of Eq. (7) and (8) yield an upper bound of $R_s = 0.213$ (for a λ^3 variation $R_s = .204$; $R_s \longrightarrow .200$ as the exponent increases). Then the formal application of Eq. (9) assuming a smooth reflector yields an upper bound on the dielectric constant of $\epsilon \leq 7.1$. The consideration of Lambert scattering requires us to increase the scattering area by 8/3; the dielectric constant is thereby reduced to $\epsilon \leq 3.2$.

Assuming that the minimum power reflection is 10% we get $\epsilon \geq 3.7$ for the smooth planet and $\epsilon \geq 2.2$ for the rough planet. These results are summarized in Table III. Typical terrestrial values of the dielectric constant taken from Kerr (1951) are presented for comparison in Table IV. It is interesting to note in passing that Hoyle (1955) has proposed a Venusian surface of hydrocarbons which have dielectric constants as low as 1.8.

IV. CONCLUSIONS

1. The proposed ionospheric model for the generation of the thermal radio spectrum of Venus is not consistent

with the radar observations.

2. The generation of the radio spectrum of Venus by any mechanism in its atmosphere which inherently depends on high opacity is highly unlikely. This conclusion tends to support the conjecture that the observed 600°K decimeter black body temperature derives from the planetary surface.
3. The Venusian atmosphere is essentially transparent at decimeter wavelengths.
4. The mean electron density of the Venusian atmosphere is probably no more than one order of magnitude greater than that for the Earth.
5. The mean dielectric constant of the Venusian surface material is probably no greater than 7.1 with an absence of large upward variations with the planet's rotation consistent with relatively dry terrestrial soils and the <u>absence</u> of large bodies of water.

ACKNOWLEDGMENTS

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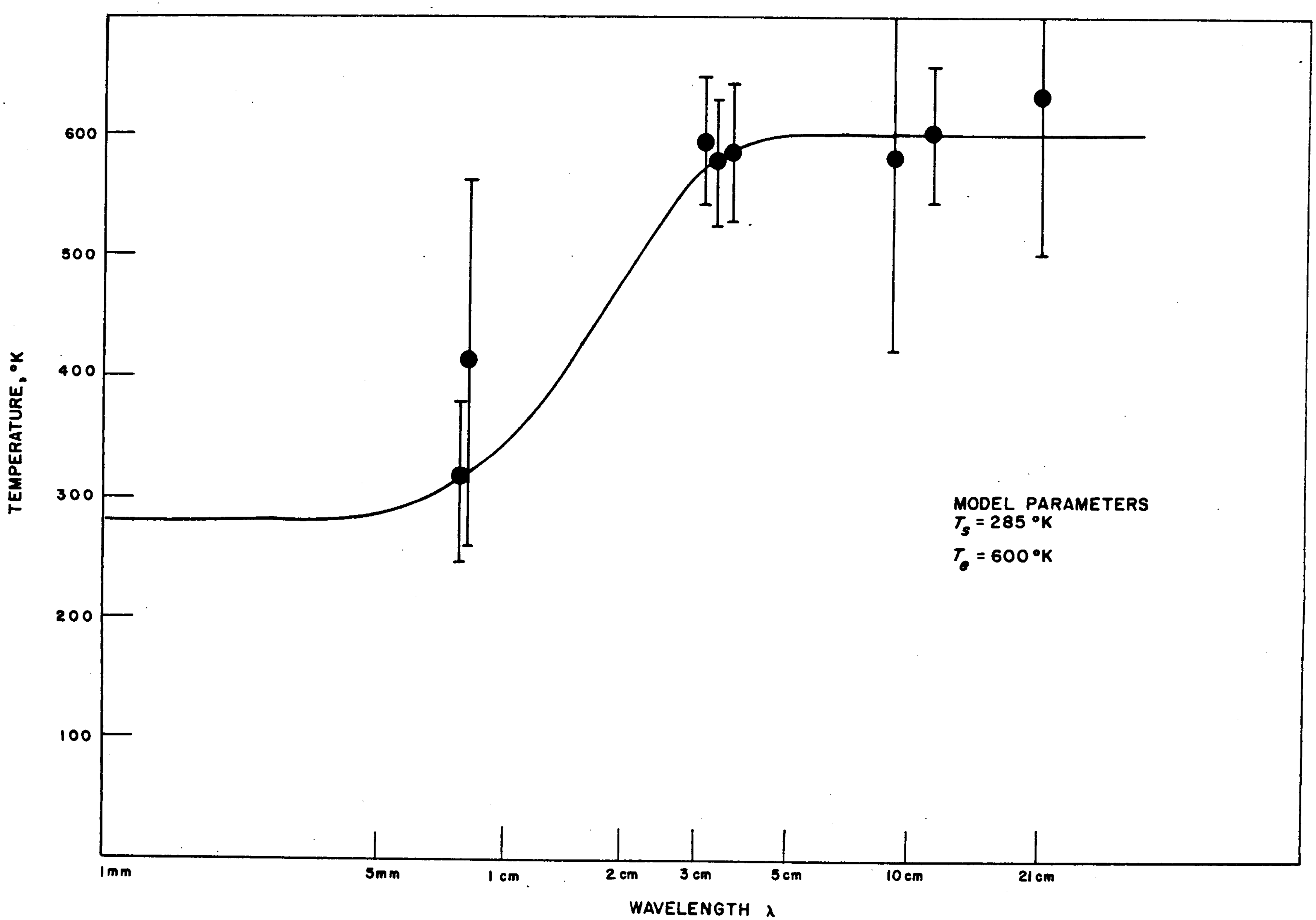
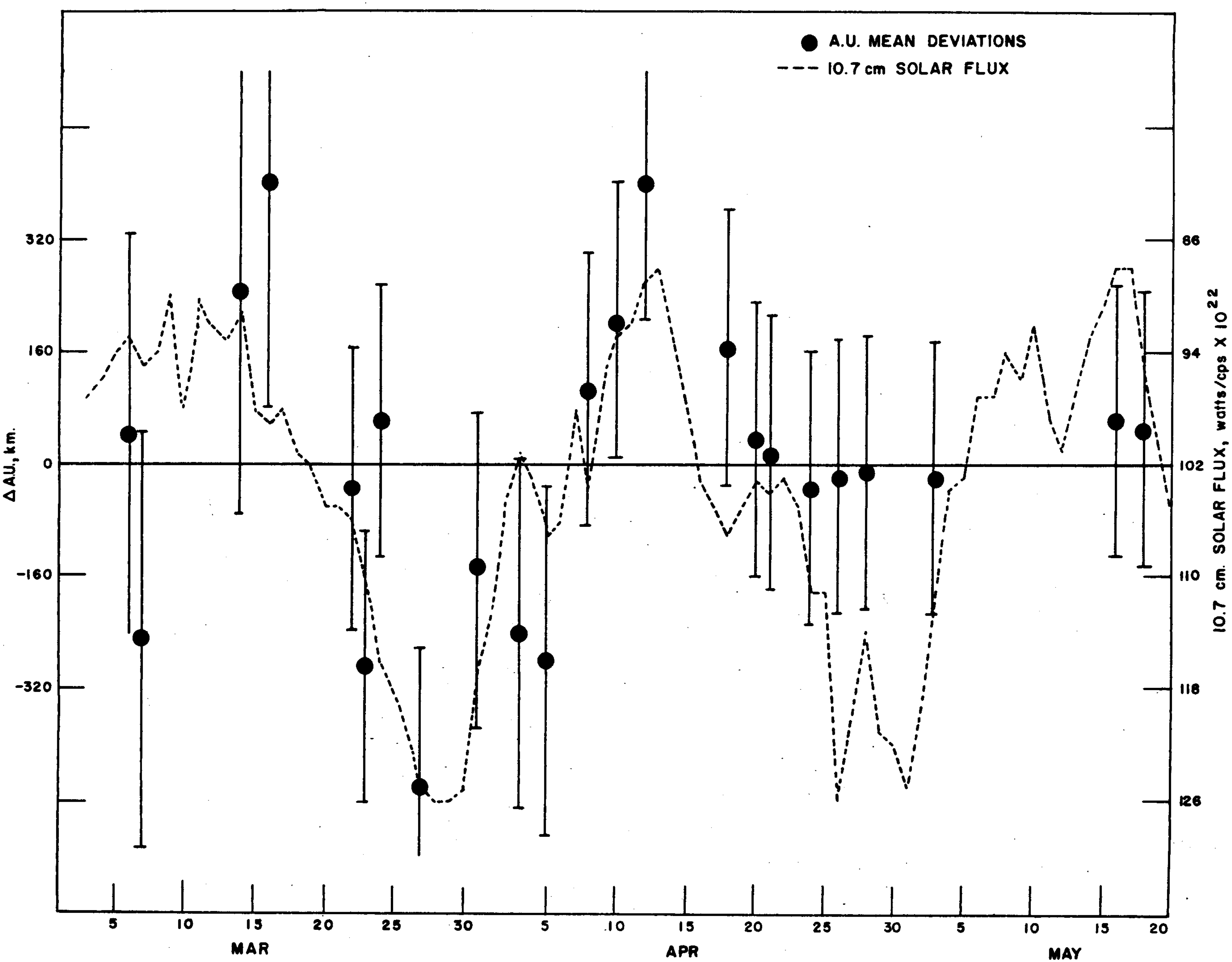
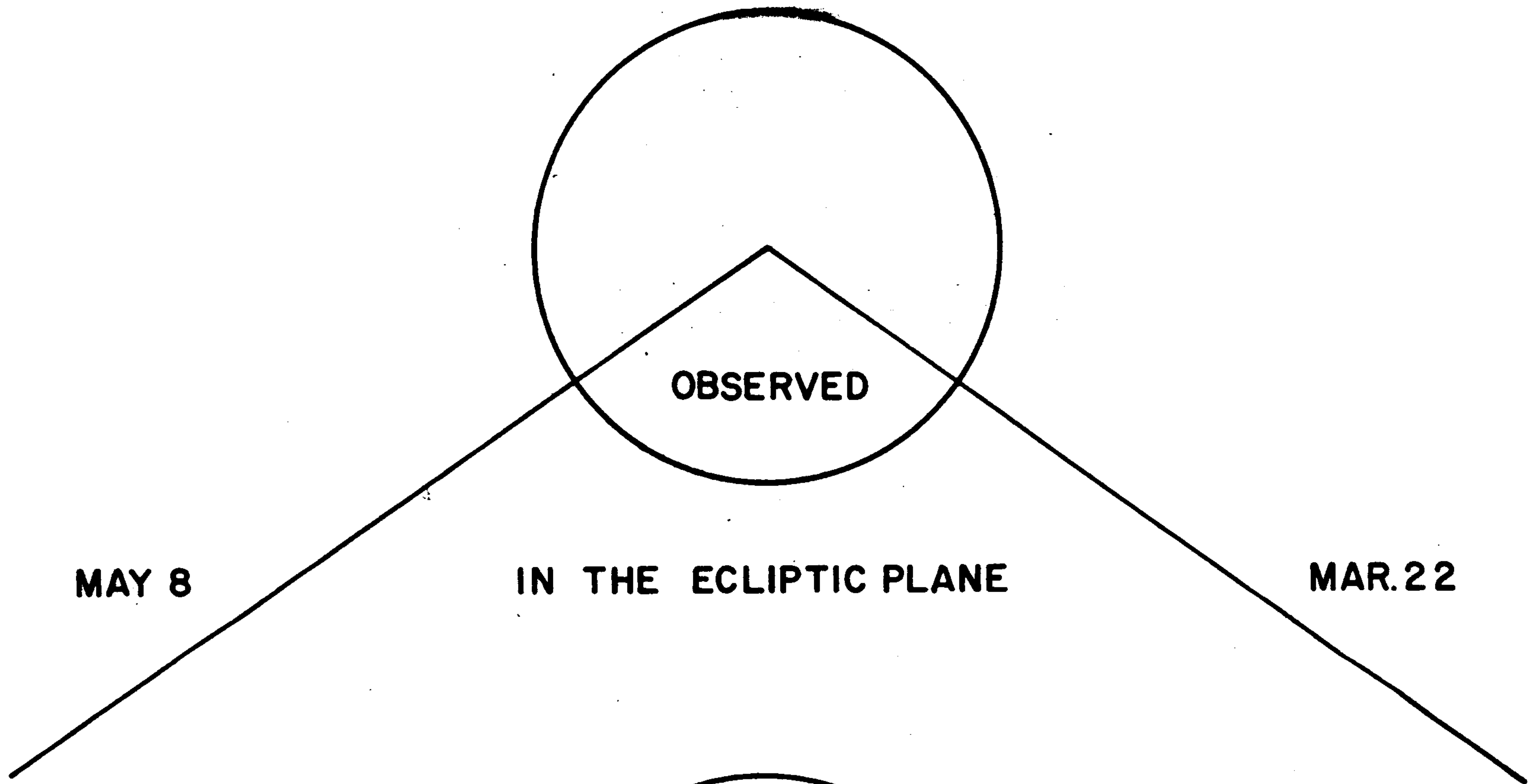
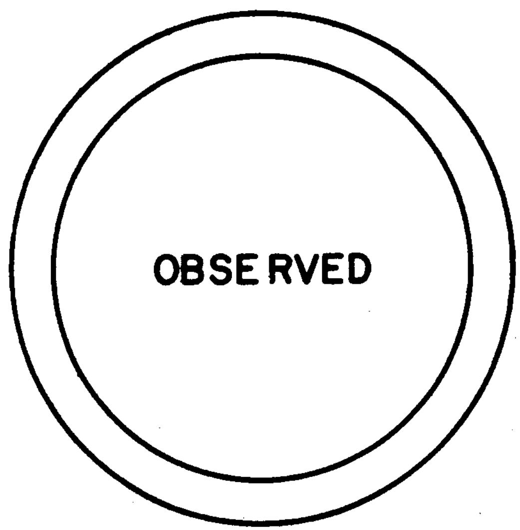
FIGURES


TEMPERATURE, °K
600
500
400
300
200
100
1mm
5mm
1 cm
2 cm
3 cm
5 cm
10 cm
21 cm
WAVELENGTH λ
MODEL PARAMETERS
T_s = 285 °K
T_e = 600 °K



A.U. MEAN DEVIATIONS
10.7 cm SOLAR FLUX
Δ A.U., km.
320
160
0
-160
-320
86
94
102
110
118
126
10.7 cm. SOLAR FLUX, watts/cps X 10^22
5
10
15
20
25
30
MAR
APR
MAY





ALONG THE ECLIPTIC PLANE

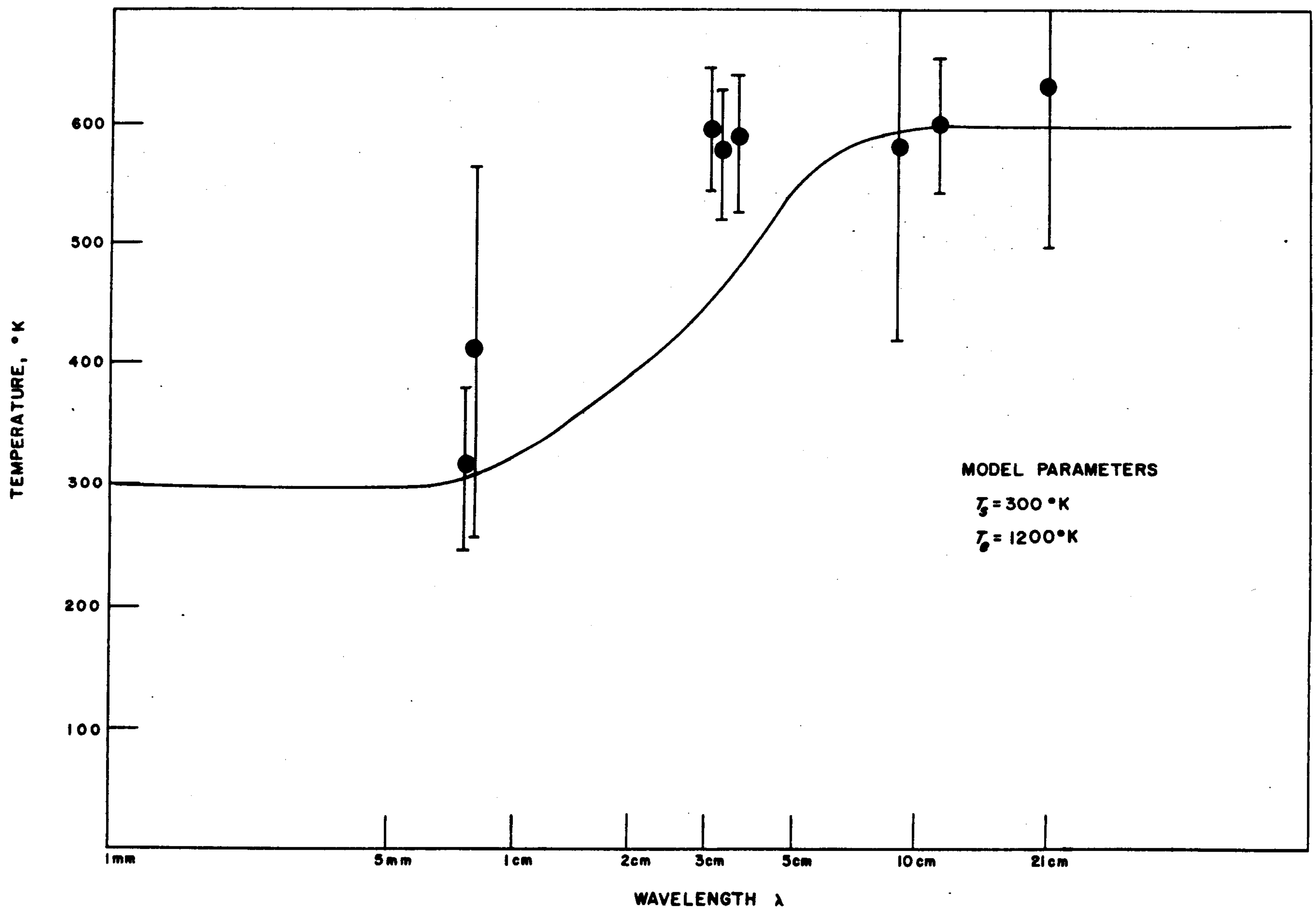

TEMPERATURE, °K
600
500
400
300
200
100
1mm
5mm
1cm
2cm
3cm
5cm
10cm
21cm
WAVELENGTH λ
MODEL PARAMETERS
T_s = 300 °K
T_e = 1200 °K

Table I. The Physical Size of the Venusian Radiating Disk Consistent with the Ionospheric Model

Electron density (cm^{-3})	Thickness (km)	Ratio of solid angle to that of the visible disk
10^7	4×10^6	4.1×10^5
10^8	4×10^4	55
10^9	4×10^2	1.015
10^{10}	4	~ 1
10^{11}	40 (meters)	~ 1

Table II. The Venusian Integrated Electron Density as a Function of the Electron Temperature

T_e(°K)	$\int N_e^2 dz$ (cm^{-5})	$\int N_e^2 dz / 10^{19}$	$N_{e\,♀} / N_{e\,\oplus}$
100	2.52×10^{21}	2.52×10^2	18.6
200	7.06×10^{21}	7.06×10^2	26.6
400	2.02×10^{22}	2.02×10^3	44.9
600	3.78×10^{22}	3.78×10^3	61.4
1000	5.55×10^{22}	5.55×10^3	74.4
2000	7.26×10^{23}	7.26×10^4	150.0

Table III. Upper and Lower Bounds on the Venusian Dielectric Constant *

Scattering law	Maximum ϵ	Minimum ϵ
Smooth sphere	7.1	3.7
Lambert sphere	3.2	2.2

*The atmospheric absorption is assumed to be strongly wavelength dependent.

Table IV. Terrestrial Dielectric Constants*

Medium	λ	ϵ
Sea water	10 cm	69
Fresh water	1 m	80
Very dry sandy loam	9 cm	2
Very wet sandy loam	9 cm	24
Very dry ground	1 m	4
Moist ground	1 m	30
Arizona soil	3.2 cm	3.2
Austin, Texas soil, very dry	3.2 cm	2.8

* Kerr (1951)

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